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The Sociology of Speed

Capital's Geodesic: Chicago, New Jersey, and the Material Sociology of Speed

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The development of the technologies for transmitting financial data is a clear demonstration of the central thesis of Wajcman's *Pressed for Time*.[1] 'Temporal demands are not inherent to technology', she argues. 'They are built into our devices by all-too-human schemes and desires' (Wajcman 2015, p.3). This chapter examines one of the most dramatic increases in speed in recent times: the shift from trading conducted among human beings at a pace they could follow, to high-frequency trading or HFT (the fast, entirely automated trading of large numbers of shares and other financial instruments), which involves speeds beyond those perceptible by human beings. To be sure, this shift has been made possible by wider developments over the past three decades in computing and communication technologies, but the speed-up of trading cannot fully be explained simply by generic technological change. As Wajcman would suggest, it also results from design decisions that are quite specific, and that reflected priorities that are different from those of the wider information and communication industries.

[1] The second section of this chapter draws upon MacKenzie (2014); I am grateful to the *London Review of Books* for permission to do so. The research reported here is part of a wider project (Evaluation Practices in Financial Markets) supported financially by the European Research Council (grant agreement no. 291733). Figure 1 was kindly produced by Taylor Spears, using the open-source application KDE Marble.

The chapter draws upon one strand of research I have been conducting over the past five years on HFT, on the streams of data and technologies drawn on in it, and on the development of the electronic trading venues on which HFT is practised. The research is primarily interview-based and, so far, largely US-focused (of the 172 interviews conducted so far, 61 have been in New York and 61 in Chicago); see Table 1 for more details, and for the two-letter acronyms used to label interviewees. (One interviewee, Stéphane Tyč of McKay Brothers, has given me his permission to name him.) The overall goal of the research is to discover how automated trading and electronic venues in which it takes place have been and are being shaped in five main markets: shares, futures, foreign exchange, US Treasury bonds, and options.

– INSERT TABLE 1 AROUND HERE –

The theoretical premise of the research is that, in order to understand financial markets, we need a *material sociology* of those markets, one that gives equal weight to each of those two words. I've explored the underlying theoretical position at length elsewhere (MacKenzie 2009), but let me summarize briefly by expressing the key point in actor-network theory terms, since that theory (for which see, e.g. Latour 1987 and 2005 and Callon 1986) is currently the most influential form taken by material sociology. The actors in financial markets are almost never 'naked' individual human beings. Rather, they are assemblages of human beings (often multiple human beings) and technical artefacts: both 'physical' artefacts — such as computers, calculators, and communications technologies — and ‘cognitive’ artefacts such as mathematical models.[2]

That has always been the case, even if artefacts of the past, both physical and cognitive, look primitive to today’s eyes. A basic postulate of the material sociology of financial markets is that artefacts matter: that different configurations of humans and physical/cognitive equipment form different actors and have different effects. That, for example, is a generalization of what has become the well known thesis of the ‘performativity of economics’: the idea that economics (understood in a broad sense, not simply as the academic discipline) is not just an external representation of markets but intervenes actively in markets, indeed is part of how markets are constructed (Callon 1998; MacKenzie, Muniesa, and Siu 2007).

It is clear that, in high-frequency trading, action flows directly from artefacts (orders to buy or sell are placed by computer systems with no direct human involvement) and indirectly from assemblages of human beings and artefacts. The firms are typically small: a staffing complement of a hundred people makes you quite a large HFT firm, possibly among the two dozen largest worldwide. (A big organization such as a bank often has an old-established, slow technical infrastructure, and banks are structured

[2] The distinction between the ‘physical’ and the ‘cognitive’ is for ease of exposition only. The brain is a material organ, and has limited processing and memory capacity. In consequence, as the literature on ‘extended’ or ‘distributed’ cognition (e.g. Hutchins 1995) emphasizes, many cognitive operations involve external equipment. For example, many of today’s mathematical models in finance cannot realistically be solved by an unaided human being: they have to run on computer systems.

bureaucratically, frequently with an IT department separate from trading teams; the combination of slow infrastructure and organizational separation makes the flexible, responsive development of fast systems hard.) The vast majority of an HFT firm's trading is initiated by its computer systems. The direct role of human beings is often restricted to monitoring the operation of trading systems and closing them down if things go wrong, for example if trading algorithms start incurring losses and for some reason do not shut themselves off. Less directly, though, humans do of course write the algorithms, and it is quite common for human beings to be allowed to select which algorithms to employ. In some 'grey box' systems (as participants call them) the human user can also choose the values of one or more mathematical parameters of an algorithm.

HFT hasn't generally speeded up the pace of human work. One consequence of the often limited direct role of human beings in HFT is that they can experience less pervasive time pressure than in older forms of trading in which humans were more central. A trading room from an earlier generation was often a busy, noisy place. Information flowed into it not just from computer screens but also via telephone calls, conversations and shouted interjections. 'Hoot-n-holler' or 'squawk box' systems – involving permanently open telephone connections among multiple traders and brokers – brought near-constant interruptions when markets were busy, and reacting to customer demands or market developments involved quick use of a keyboard or a succession of rapid telephone conversations. In contrast, the trading rooms of HFT firms are usually quiet — in my visits to them, I've never heard anyone shouting; phones almost never seem to ring — and while some traders can be seen focused intensely on computer screens, others have time to chat. The typical atmosphere of such rooms resembles that of a high-technology start-up company more than that of a traditional trading floor. With machines doing the direct trading, human traders can in many cases simply keep a loose eye on them while also (as interviewee AV put it) working on 'long-term projects': researching and developing new trading algorithms.

Rather, the speed-up is of HFT as a material, technological practice. What follows focuses on one very specific aspect of that material practice: the communications links between the Chicago futures markets and the computer datacentres in New Jersey in which shares – and also Treasury bonds, foreign exchange and stock options – are traded. (If space permitted, a broadly similar account could be given of other crucial links, for example those that interconnect the New Jersey datacentres or the transatlantic submarine cables.) The next two sections of the chapter explore the changing material forms of those links and how, as Wajcman might suggest, those forms have been and are being deliberately shaped for speed. There are trade-offs in the design of any technical system – interviewee SO, a specialist in telecommunications links for finance, quoted an engineer's saying: 'you can make it fast, cheap or reliable, pick two' – and the trade-offs made in the design of the Chicago-New Jersey links discussed in this chapter quite consciously prioritized speed. The chapter's final section then emphasizes that, though those links are shaped intimately by the physical world and our knowledge of it, they are not 'mere physicality': they are also social in at least four different senses.

Transmitting Prices from Chicago to New Jersey by Fibre-Optic Cable

It's very tempting to theorize globalization as involving time speeding up and space shrinking (see, especially Harvey 1989). In respect to trading, however, that formulation is only half right, as is pointed out in MacKenzie, Beunza, Millo, and Pardo-Guerra (2012): precisely because the material activity of automated trading has speeded up dramatically, so geography and spatial distance — where exactly places are, and the shortest route between them — have taken on a new significance. The shortest, and therefore the fastest, route on the surface of the earth between any two places is what's called the 'geodesic' or great-circle route. The world's financially most crucial geodesic — the spinal cord of U.S. capitalism — runs from Aurora, a town in Illinois that's now an outer suburb of Chicago, to northern New Jersey.

– INSERT FIGURE 1 AROUND HERE –

Aurora matters to global finance because in 2012 the CME, the Chicago Mercantile Exchange, relocated its electronic trading system to a new data centre there. (Earlier, its trading system and thus the start of the crucial geodesic was in a data centre called Cermak, just south of the Chicago Loop.) The CME trades futures: at first, futures on eggs, onions and other agricultural commodities, but since 1972 financial futures as well. Originally, Chicago futures trading was done face-to-face (by voice, or eye-contact and hand signal) in raucous, crowded trading pits. The CME's pit traders fiercely resisted the coming of electronic trading: its leading advocate, Leo Melamed, received frequent death threats. By 2004, however, that resistance had crumbled, and now nearly all the CME's trading is electronic. (For discussion of the processes of change, see MacKenzie 2015.)

The CME's first fully electronic product was the E-Mini financial future, launched in 1997. It tracks the S&P 500 index, made up of the 500 leading U.S. stocks. The buyer and the seller of an E-Mini each maintain a deposit known as 'margin' on account at the CME's clearing house. Every night, the clearing house adjusts those deposits. If the S&P 500 index has risen by a single point, $50 is transferred from the seller's account to the buyer's; if it has fallen by ten points, say, $500 shifts from the buyer to the seller. If their deal is for a thousand E-Minis, the latter sum becomes $500,000. (The contract is called the 'Mini' or the 'little' because these transfers were five times larger for the contract that traders called the 'big', the corresponding pit-traded S&P 500 future.)

Both the literature of financial economics (e.g., Budish, Cramton, and Shim 2013) and traders themselves in interview report that new information relevant to the overall value of U.S. shares tends to show up first in orders for and in the prices of the E-Mini, and only a fraction of a second later in the underlying shares.[3] The likely reason is that the E-Mini gives greater 'leverage': a modest 'margin' deposit permits gains (and, of course, also losses) corresponding to buying or selling a large and expensive block of shares. So if traders think that they or their automated trading systems have an information

[3] There is some suggestion in one of my more recent interviews (BU, interviewed in June 2015) that this pattern may be being replaced by more of a two-way interaction.

edge, it has traditionally been to the E-Mini that they will usually turn first. For example, the big crises of modern US stock markets have tended to show up first in the E-Mini (or, before 1997, in its predecessor, the S&P 500 pit-traded future) and only a little later in the stock market.

Changes in the electronic order book for the E-Mini are crucial information for automated share trading (this particular game is now too fast for human players, who wouldn't be able to react quickly enough to those changes). Suppose the price of the E-Mini has fallen, or even simply that the number of offers (sell orders) has risen sharply and the number of bids (buy orders) has fallen. Over the next fraction of a second, falls in the prices of the underlying shares are more likely than increases.

The fact that changes in Chicago's futures order books and prices are closely linked to, and generally precede, changes in share prices makes the transmission of futures data to the datacentres in which shares are traded a crucial matter. Originally mainly in New York, those datacentres are now in New Jersey, where real estate is cheaper. For more than a decade, there have been concerted efforts to speed transmission from Chicago to New Jersey. By the time the E-Mini was launched in 1997, state-of-the-art transmission was via fibre-optic cable. That is intrinsically very fast: light signals in optical fibre travel at around two-thirds of what the theory of relativity posits as the fastest possible speed, that of light in a vacuum. For nearly all human purposes, therefore, the existing network of fibre-optic cables was fast enough, and the telecoms firms that had created that network had not been concerned with achieving further increments in speed. Rather, they chose paths (such as alongside railway lines) along which it was easy to negotiate permission to lay their cables, and shaped their networks so that they served the maximum number of large population centres. As will be discussed below, they also prioritized ease of repair over minimum cable length.

By the early 2000s, however, HFT firms were beginning to focus on the fastest possible transmission from Chicago to the East Coast datacentres in which shares are traded. To begin with, it was difficult for them to get the telecoms companies even to understand their resultant concern with matters such as specific cable routes. They couldn't go to a company such as Verizon and ask for the fastest route:

> you could go to your Verizon salesperson, and they had no such product in their catalogue. They just sold circuits. The Verizon provisioning systems … didn't have the capacity to actually understand shortest path. They just knew you wanted a T-1 or a T-3 [or] whatever between point A and B, and they would provision on whatever [cables] happened to be available. And by the way, they would reprovision it [shift to different cables] if they needed to do some load balancing … they never actually thought that anybody cared [about the exact physical route]. (Interviewee SO)[4]

[4] T-1 (Transmission System 1) was the original 1962 AT&T digital-transmission specification, which was later re-implemented for optical fibre. T-2 and T-3 are higher-capacity versions.

There were, nevertheless, databases of fibre-optic cable routes, including one constructed by CFN, a specialist network firm based just outside of Washington, DC. Using CFN's database, along with trial-and-error testing, a Chicago HFT firm discovered, in the early 2000s, an old cable laid several years earlier between Chicago and the East Coast by the pioneering Internet service provider UUNET.[5] From a standard telecommunications viewpoint, the cable was unimpressive. Its bandwidth (capacity) was limited, and to save money, UUNET had simply buried the cable in the soil, rather than laying it in conduits as was normal practice. However, UUNET had also sought to cut costs by choosing as short a route as reasonably feasible, largely following power lines across the countryside. That meant that the inferior, old cable was actually the fastest route between Chicago and New York/New Jersey. Eventually, the HFT firm succeeded in persuading the cable's then owner to lease it to the firm, and the resultant capacity of the firm's East Coast computer systems to receive Chicago prices faster than other systems helped it become a dominant player in share trading.

The next stage in the technological evolution of Chicago-New Jersey communications is the best documented (Steiner 2010; MacKenzie, Beunza, Millo, and Pardo-Guerra 2012; Lewis 2014). It began with trader Dan Spivey's realization that existing routes were not the fastest possible (even the UUNET cable was still at some distance from the geodesic), and that a new cable closer to the geodesic was a commercially attractive proposition: any HFT firm whose

[5] My main source here, interviewee SO, said that 'couple' of firms discovered this cable, but other sources (interviewees AF and BQ) indicate that one particular firm gained control of this route.

algorithms depended on the fast transmission of prices between Chicago and the East Coast would *have* to use it, and would therefore be prepared to pay high fees to do so. With funding from the venture capitalist James Barksdale, Spivey's firm, Spread Networks, negotiated with dozens of local governments and landowners the rights to lay a new, more direct cable. Closeness to the geodesic brought physical difficulties – the Allegheny Mountains lay in the way (although interviewee SO reports that the extent of drilling through rock is implicitly exaggerated in existing accounts) – but Spread Networks overcame those difficulties, and also succeeded in keeping the project secret until shortly before its completion. The firm spent at least $300 million (one interviewee suggested it may have been as much as $500 million) laying the new cable, but its bet that HFTs would have no alternative but to pay large sums to lease strands of fibre in the cable from Spread turned out to be correct: former high-frequency trader Peter Kovac (2014, p.3) reports that the fee was $176,000 per month, with a requirement to enter into leases several years long.

The new cable, which began to operate in August 2010, runs from Aurora through Chicago to Cermak, then along the south shore of Lake Michigan, across rural Indiana and Ohio, along the south shore of Lake Erie, and then across rural Pennsylvania to Carteret, New Jersey (the site of Nasdaq's datacentre), before finally turning north to 165 Halsey Street (the datacentre in Newark that is New Jersey's main telecoms hub) and then the other New Jersey financial datacentres and Manhattan. This close-to-geodesic routing became its most celebrated feature. However, the prioritization of speed had other manifestations not discussed in the existing literature on the cable.

First, when laying a normal telecommunications cable (see, for example, Figure 2), standard practice was and is for construction crews to add considerable slack (typically 5-10 percent of a cable's total length):

> [W]hen you run fibre you put slack in … you take the cable and you just coil it up at each of [the amplifier] centres or … in manholes, and the reason you do that is because every once in a while the fibre gets cut. Someone is doing construction, a train derails, a bridge abutment erodes, whatever, and the cable breaks … What you want is a cable that's a little loose and you can pull the two ends together, splice them together, and you're good to go. (Interviewee SO)

Spread Networks deliberately used much less slack:

> [A]t Spread there was a constant fight with the construction crews because they wanted to do what they've always done: 'Why wouldn't you want slack in the network?' They didn't understand latency considerations: 'Why do you care about a few microseconds [millionths of a second]?' (Interviewee SO)

– FIGURE 2 AROUND HERE –

Second, when optical fibre is used to transmit signals over large distances, those signals need amplified at intermediate points. As the Spread Networks cable runs across Indiana, Ohio, and Pennsylvania, there are eleven such points, which take the form of concrete bunkers. An HFT firm that leases a fibre in the cable needs to run that fibre through an amplifier in each of the bunkers. A telecommunications firm would place a general-purpose switch in each bunker so as to facilitate network interconnections, for example to nearby towns. Those switches, however, slow transmission, so the HFT firms using the Spread cable ‘would basically go just either straight optical-to-optical [amplification] or a very simple, lean electrical-to-optical and straight back, not going through a general switching fabric’ (interviewee SO).

Third, modern fibre-optic transmission employs ‘dense wave division multiplexing’, in which there are multiple channels of communication on a single fibre, which are kept from interfering with each other by the fact that a different wavelength of light is used for each. A telecommunications firm will want to maximize the bandwidth (capacity) of the fibre, so might use as many as a hundred different channels with different wavelengths. The firm will accept the fact that this dense packing causes a small amount of interference to take place, and to compensate for that will employ software that processes the messages being transmitted, adding extra binary digits to them that enable errors in transmission to be detected and corrected. This ‘forward error correction’, as it is called, slows transmission, so HFT firms generally do not employ it. Instead, they pack many fewer communications channels (perhaps as few as ten) into a single fibre of the Spread cable.

Speed, however, was not the only imperative that imposed itself on the Spread cable: the other (perhaps surprisingly) was perceived fairness. It would have been hard to recruit subscribers if they had feared that other subscribers would still be able to have a speed advantage. So Spread devoted considerable effort to ensuring that this would not happen to a subscriber who paid for premium access.[6] The most important issue in this respect was paying close attention to the paths followed by different strands of fibre in each of the eleven bunkers, so as to ensure those paths were of equal lengths. Each bunker was only around 15 metres long, but as interviewee SO put it, ‘the reality is you’re going up, down, and across, and so on. And if you do that eleven times it starts to add up’. (The focus on this issue indicates the sensitivity of speed. Even ‘adding up’, any path difference was likely to be only a small number of metres at most, and a signal moving at two-thirds of the speed of light in a vacuum travels 200,000 kilometres – 200 million metres – in a second.) So important was fairness that even the slight physical inhomogeneity of the material making up the different strands of fibre was compensated for, with the strands that had marginally lower refractive indexes made ever so slightly longer (by a small amount of coiling if necessary) to ensure transmission times that were as equal as possible.

When Two-Thirds of the Speed of Light is Not Enough: The Shift to Microwave

What Spread Networks could do little about, however, was the basic physical effect that slows the transmission of light in optical fibre. Spread used TrueWave® RS fibre, which was the fibre with the lowest refractive index (and thus the highest transmission speed) that could be employed without increasing the number of bunkers. Its refractive index, however, is around 1.47 (Lucent

[6] There was a second tier of subscribers who paid lower fees, but experienced a transmission time around a millisecond slower than the premium: ‘there was literally a cabinet that the fibre just went around and around and around until it added a millisecond in … delay’ (interviewee SO).

Technologies 1998; the exact value depends on the wavelength being used), which means that light travels in it at just over two-thirds of its speed in a vacuum: see Table 2.

– INSERT TABLE 2 AROUND HERE –

There was a much older form of data transmission that did not have this drawback: radio transmission through the atmosphere, especially using microwaves transmitted along a series of towers (see Figure 3). The refractive index of the atmosphere varies with air pressure and temperature, but close to the earth's surface it is typically around 1.0003, meaning that wireless signals travel at around 99.97 percent of the speed of light in a vacuum. That physical fact was well known (for example to those who designed the Spread cable), but they also knew that because of the curvature of the earth, multiple towers with microwave repeater equipment were needed. This equipment introduced delays that – although imperceptible to human senses and of no consequence in the normal uses of microwaves in telecommunications – more than used up any speed advantage that microwave might have over the new cable.

– FIGURE 3 AROUND HERE –

At least three people, however, realized that delays in repeater equipment might simply be the result of its designers not focusing on speed. One was a Soviet-educated computer scientist, Alex Pilosov, who had emigrated to the United States, did consultancy work for various Wall Street banks, and had set up a business as a high-speed internet provider; the others were Robert Meade and Stéphane Tyč, both physicists who had done extensive work in finance. Their enquiries to manufacturers about how fast their repeater systems were met with first incomprehension – 'they would not understand the question' – and then inability to answer: 'the radio manufacturers did not even know how fast they [the repeater systems] were' (Tyč interview).

Pilosov found a small Czech company whose repeater equipment was fast by the standards of the day; as with the UUNET cable, its speed was an accidental by-product, in this case of the simplicity of its design. He paid the company to change its equipment to increase the speed further, and raised funds (by selling his house, borrowing as much as he could, and finding an HFT firm to back him) to construct a microwave link from Chicago to New Jersey. There was a plethora of existing microwave towers that could be used, but considerable work (largely done by Pilosov himself) was needed designing the network: researching feasible routes; checking that interference with other signals would not be a barrier to approval from the Federal Communications Commission; doing the structural calculations to show that the towers were strong enough to support the new microwave dishes; and persuading municipalities to give their permission to install them. By 2010, however, Pilosov had his new link up and running.

Meade and Tyč had met as physics PhD students at Harvard University, and the two closely linked firms they set up, McKay Brothers and Quincy Data, were named after Harvard's Gordon McKay Applied Science Laboratory and Quincy House. They were better resourced than Pilosov, and worked more slowly: they were aware that their new link would face eventual competition, and focused on designing it in such a way that it would be very hard for a competitor to be as fast or faster. To do so, they had to break with existing traditions of microwave network design, which had placed great emphasis on reliability and virtually none on speed:

> [W]e realized … that networks did not have to be designed in the 'old and conservative way'. Microwave engineers had applied recipes which worked perfectly but which imposed constraints that we relaxed. This relaxing of engineering constraints allowed [us] to focus on the most important constraint for us which was the total path length. We ruthlessly optimized this parameter to create a long lasting network. (Email from Tyč, 1 October 2014)

Meade and Tyč placed some of their repeater stations much further apart than had been previous practice. Doing this minimized the number of stations and thus the delays they caused, but it was also necessary because a route close to the geodesic involved a lengthy crossing of Lake Erie (and in the case of signals from Cermak, also Lake Michigan): see Figure 1. Their longest 'hop' – gap between towers – was around 110 km. 'Most microwave engineers will tell you that this is crazy stupid,' says Tyč, because those engineers believed that transmission would become unreliable or even infeasible over that distance (Tyč remembers one engineer even 'saying that microwave links over 50 km were not possible'). Meade and Tyč's understanding of the physics of microwave transmission, however, made them confident that their long lake-crossings were feasible.

The pursuit of speed required more than simply long hops. The US Federal Communications Commission makes a number of wavelengths available for microwave networks, including 6 GHz (gigahertz), 11 GHz, 18 GHz, and 23 GHz. From the viewpoint of the reliability of a microwave link, 6 GHz is best: as frequency increases, links become more vulnerable to disruption by rain. If, however, McKay Brothers had restricted themselves to 6 GHz they would have had to depart from the geodesic: part of the process of getting the Federal Communications Commission's permission to create a new microwave link is an analysis of whether it is likely to interfere with existing links, and there were simply too many existing 6 GHz links close to the geodesic. So Meade and Tyč's firm used not just 6 GHz but also some 11, 18, and even 23 GHz frequencies to keep their route as close as possible to the geodesic, even though they knew it increased the likelihood of disruption by rain. '[W]e had a little motif: better be first 99 percent of the time than second 100 percent of the time' (Tyč interview).

The new McKay Brothers link, completed in 2012 but reworked almost continuously since then, has indeed remained in general the fastest (the HFT firm that had gained control of the UUNET cable built its own microwave link from Chicago to New Jersey, and it briefly surpassed McKay Brothers in speed in late 2014). The McKay Brothers' link also achieved, and indeed soon considerably surpassed, the firm's goal of 99 percent availability. Nevertheless, it (and the other microwave links between Chicago and New Jersey, including that created by Pilosov) still remain to some extent vulnerable to the physical world: to rain, to gales – which can blow microwave dishes out of alignment and make it unsafe for workers to climb the towers to realign them – and even to lightning (interviewee SL reported that his firm's equipment on one tower was 'fried' by a lightning strike because thieves had stolen the copper grounding wire). Even the benign summer sunrise and sunset over the Great Lakes can be a problem for some networks: it can heat the upper atmosphere more than the lower, changing refractive indexes in a way that causes microwaves to 'bend up', and 'then line-of-sight is shorter than expected', which can cause a link temporarily to fail (email from interviewee SL, relayed by my colleague Alexandre Laumonnier).

The Material and the Social

As Tyč put it, in what turned out to be the first of three interviews with him: 'in the end, all [trading] firms will need to have some kind of microwave service. Otherwise they'll base their decisions on stale data. It's as simple as that, really. It's physics.' As the previous two sections of this chapter have shown, the physics of data transmission along capital's geodesic is indeed important. Meade and Tyč's background as physicists also helped give them the confidence to depart from standard practices in microwave engineering. But what is at stake is not simply physics.

First, physical processes are intertwined with economic ones. Laughlin, Aguirre, and Grundfest (2012) show that the two most consequential changes in transmission technologies from Chicago to New Jersey – the opening of the Spread Networks’ cable in April 2010 and of the McKay Brothers’ microwave link in August 2012 – had effects that can be traced in the movements of US share prices. As Laughlin and his co-authors put it, ‘an appreciable fraction of the entire U.S. equities market responds … to just a few bits of information emanating from suburban Chicago and travelling via various channels and between 4-10 milliseconds, to suburban New Jersey’ – and the speed with which it does so increased as state-of-the-art transmission times have fallen as sketched in Table 2. That is an effect of ‘the technological’ on ‘the economic’, but traders’ anticipation of that effect was of course what led to the economic investments that created the Spread cable and the various microwave links.

One of Tyč’s firm’s clients told him ‘that there is a new saying’ in the markets: ‘when it rains, the spreads are higher in New Jersey’, in other words automated trading systems in the share-trading datacentres in New Jersey post less aggressive prices (bid and offers that are not as close to each other) when the microwave links from Chicago – and perhaps also the millimetre wave links among the New Jersey data centres, which because of the high frequencies they use are especially vulnerable to rain (MacKenzie 2014) – are disrupted. Of course, that is simply an anecdotal observation, not an econometric finding, but the fact that it is said, and is plausible, demonstrates the interweaving. Just as the pursuit of speed has given spatial location renewed importance, so it has created a link between financial markets and weather whose existence in the twenty-first century is striking.

Second, as I have emphasized, the pursuit of speed of transmission of price data from Chicago to New Jersey has involved conscious trade-offs (for example between speed and reliability, and speed and ease of maintenance), resulting in design decisions that were different from those typical of the wider communications industry. The resultant fibre-optic and microwave links along capital's geodesic are thus 'socially shaped', to use an old expression from the sociology of technology (MacKenzie and Wajcman 1985): their design, and the priorities manifest in it, bear the imprint of the circumstances of their creation.

Third, the circumstances that have led to these substantial technological enterprises are an example of what (Krippner 2001, p. 785) calls 'congealed … struggle'. The details of that struggle cannot be treated here (they will be discussed in MacKenzie forthcoming), but its core was the long-standing desire of Chicago's futures markets to trade stock-index futures. For decades, that desire had been blocked by the fact that, because an index is a mathematical abstraction, it is extremely clumsy to settle a futures trade on an index by anything other than a cash payment from the buyer to the seller (or vice versa). US law, and indeed the law of many countries, considered a futures contract that can be settled only in cash as a wager, and therefore illegal under the law of Illinois and indeed of most states of the US. Circumventing this obstacle was a tortuous and conflictual process that involved the creation of a new Federal regulatory body, the Commodity Futures Trading Commission (CFTC), via legal amendments in 1974 to the Commodity Exchange Act. The latter is a Federal act that pre-empts state law, and there is no Federal ban on gambling, which made activities within the domain of the new regulator (including trading cash-settled stock-index futures) legally permissible.

Hence capital's geodesic. Because US futures trading has been dominated since the nineteenth century by Chicago, the geodesic begins there. As noted above, US shares were and are traded almost exclusively on the East Coast; hence the geodesic's end-point. It is also important that this share trading falls within the jurisdiction of a different, and often a rival, Federal regulator, the Securities and Exchange Commission. (The SEC and CFTC fought repeated 'turf wars' – some even ending up in the courts – concerning jurisdiction over products such as stock-index futures that straddled their domains.) It may seem odd that two intimately interlinked sets of financial instruments (stock-index futures and stocks) should have separate, sometimes rival regulators, but the division between the Securities and Exchange Commission and Commodity Futures Trading Commission is deeply entrenched, and reinforced by the geographic separation: if it were proposed to roll the CFTC into the much larger SEC, fierce resistance could be expected from Illinois's Congressional delegation. It also matters that the SEC reports to the Senate Banking Committee, while the CFTC reports to the Senate Agriculture Committee (the origins of US futures trading lie in agricultural products), giving the two regulators separate political power bases.

The fact that futures trading and share trading fall under different regulatory regimes permits the former's leverage advantage (referred to above), which is what has made futures prices a strong predictor of share-price changes. Since the Great Depression, the extent to which US shares can be traded using borrowed money (a process that contributed to the 1929 Crash) has been tightly controlled, reducing the 'leverage' available to those trading shares. In contrast, the 'margin' deposits required in futures markets have historically been much lower, so a futures contract economically equivalent to a large block of shares can be traded with much higher leverage than could be employed in trading the block directly. This economic relationship is specific to the 'congealed struggle' just described. For example, the relationship between Treasury bond futures and the underlying bonds is more two-way, because high-leverage trading of Treasury bonds is possible using the collateralized borrowing arrangements known as 'repo' (interviewee AC; Brandt, Kavajecz, and Underwood 2007). The relationship between currency futures and currencies is, if anything, the reverse of that in shares, because big banks can trade currencies with no margin deposits at all, and thus in effect with infinite leverage. So price changes in currencies tend to lead changes in currency futures, reported interviewee AV.

Fourth, the facts that changes in the order books for US stock-index futures have tended to lead changes in the markets for the underlying shares (and that futures data can be transmitted from Chicago to New York and New Jersey fast enough to make profitable trading possible) have been an important contributor to a change in the very nature of share trading. Over the past thirty years, new share-trading actors (in the actor-network-theory sense) have come into being, involving different configurations of human beings and non-human artefacts: high-frequency trading algorithms. To be profitable, the latter need to be able to predict price changes, not on the basis of subtle, human phenomena such as a fleeting look of fear on a fellow trader's face or a change in the 'feel' of a trading floor, but using relationships of a quite different sort: relationships that can be programmed not just into a computer system but in many cases into one that is simple enough to be very fast.[7] The relationship between futures and the underlying stocks is by no means the only such relationship (others are described in MacKenzie forthcoming), but historically it was the most important resource for price prediction. It was central, for example, to the algorithms of Automated Trading Desk (set up in Charleston, SC, in 1988 and in a sense the first ever HFT firm: see MacKenzie forthcoming) and to those of the futures trading firms that in the 2000s established dominant positions in share trading.

The rise of these new algorithmic actors – now to be found not just in the futures markets and stock markets, but also in the trading of Treasury bonds, options and foreign exchange, and in Europe, East Asia, and Brazil, not just in the US – has changed many financial markets utterly. In stock markets, for example, a 'topological' shift is underway, already largely complete in the US, less so in other countries. The shift is from trading as an activity conducted 'inside' exchanges, to exchanges and other trading venues being 'nested' within

[7] A story roughly equivalent to that of communications technology could be told for the computer technology employed in HFT, where there is an increasingly tendency to minimize the use of the main memory and central processor unit of general-purpose computer systems and to use simpler but faster hardware, especially FPGAs (field-programmable gate arrays): see MacKenzie (2014).

trading, in the sense that those venues now have to compete fiercely for market share, and to do that they have to provide the technical features that facilitate the operations of algorithmic actors (MacKenzie and Pardo-Guerra 2014).

This topological shift is an example of why a material sociology of markets – including a material sociology of ultrafast trading – is needed. Epochal changes are taking place in finance, and to understand them we have to examine markets as embodied, physical, and technological phenomena, not simply as 'social' or 'economic' phenomena (if those terms are understood in abstraction from the technological). The story of capital's geodesic is thus emblematic of wider shifts in finance that urgently require analysis, especially from the viewpoint of the sociology of speed.

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High-frequency traders (AA-BV)	48
Exchange and trading-venue members and staff (EA-FY)	51
Dealers, brokers, and broker-dealers (DA-DR)	18
Institutional-investment firms' traders (IA-ID)	4
Practitioners of other forms of algorithmic trading (OA-OM)	13
Manual traders (MA-MG)	7
Suppliers of technology and telecommunications links to HFT (SA-SO)	15
Researchers/market analysts (RA-RP)	16
Total	172

TABLE 1 The overall set of interviewees.

Interviewees are identified by two-letter acronyms (specific to each category) in chronological order by the date of the (first) interview with them. E.g., AA is the first high-frequency trader interviewed (in April 2011); BV is the most recent (in June 2015).

Prior to Spread Networks	c. 8 ms
Spread Networks (August 2010)	6.65 ms
Limit in glass fibre (refractive index 1.47)	5.78 ms
Best current microwave (2015)	c. 4.2 ms
Relativistic limit	3.93 ms

TABLE 2 State-of-art one-way transmission times, Aurora, IL to Carteret, NJ (the location of Nasdaq's data centre) in milliseconds (thousandths of a second). The relativistic limit is the time that would be taken by transmission along the geodesic if it took place at the speed of light in a vacuum.

Sources: Laughlin et al. (2012) and miscellaneous.

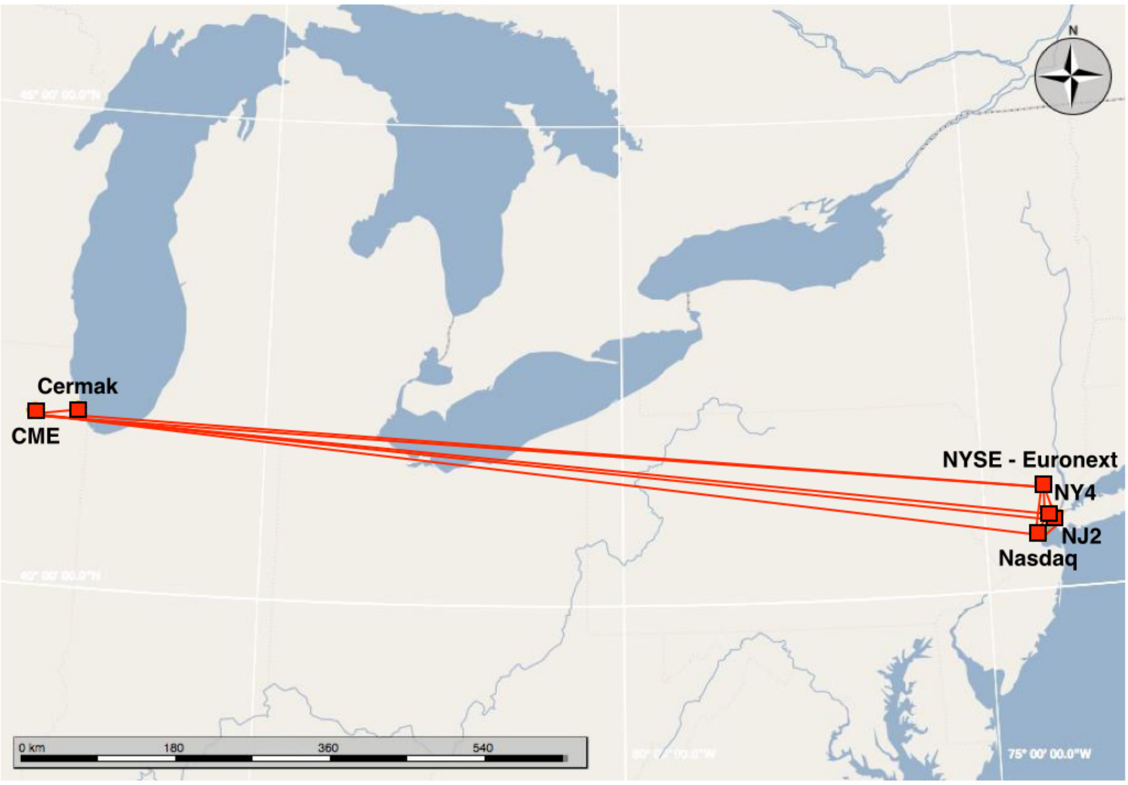

FIGURE 1 The six main financial data centres in the US. ‘CME’ is the data centre of the Chicago Mercantile Exchange in Aurora, IL. The four data centres in New Jersey are where shares (and in the case of NY4, in Secaucus, NJ, bonds, foreign exchange, and options as well) are traded.

FIGURE 2 Fibre-optic cable being laid by a construction crew working for Skanova, a subsidiary of TeliaSonera. Courtesy TeliaSonera.

FIGURE 3 A microwave tower used by McKay Brothers. Courtesy McKay Brothers.